Rehabilitation of Flood-Damaged Hydroelectric Generators

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Abstract - On October 2, 1998, the Bureau of Indian Affairs' Headgate Rock Powerplant experienced a massive breach of the penstock due to failure of the stub shaft of generating unit 2. The turbine shaft failure resulted in destruction of the turbine shaft seal, thereby allowing water into the powerplant via the turbine pit. The water level in the plant reached tailwater elevation, inundating the three generating units and excitation gallery, and partially flooding the station service gallery. The plant was under water for 2 weeks. This paper will describe the procedures used to clean, dry, repair, and test the generator stators in order to rehabilitate the units and return them to serviceable condition.

I. BACKGROUND

Headgate Rock Powerplant is located on the Colorado River in southwestern Arizona. It was designed and built by the Bureau of Reclamation on behalf of the Bureau of Indian Affairs. The outdoor plant is equipped with three identical horizontal shaft hydroelectric generators. The stator windings for the generating units were manufactured by Villares, Inc. of Brazil under a subcontract with Voith Hydro. The wye-connected three-phase stator windings are rated 4160 V rms line-to-line, 7.222 MVA, 0.9 power factor. The generating units were placed in service around 1992.

Each stator winding phase consists of four parallel circuits, with 45 coils connected in series per parallel. The four-turn stator coils are made up of rectangular copper strands insulated with thermally-fused glass and polyester fibers. The Class F groundwall insulation is comprised of resin-rich mica paper tapes. No information from the manufacturer was available to determine whether the resin used to impregnate the tapes was polyester- or epoxy-based.

Originally, two adjacent layers of strand insulation served as the turn insulation in all three generating units (contrary to the winding specification requirements). However, due to numerous turn-to-turn insulation failures experienced by unit 3 during acceptance testing, the stator of this generator was rewound with new coils having dedicated mica-tape turn insulation. Units 1 and 2 passed the acceptance tests and were not rewound. Nonetheless, the winding manufacturer was required to supply a complete set of spare coils in the event that additional repairs or another premature rewind would be necessary. During the 7 years of operation prior to the flood, no in-service failures occurred in any of the units.

II. REHABILITATION

Preliminary Assessment

After the flood water was completely pumped out of the plant, the generator stator housing and air deflector covers were removed from each of the three generators, and the stators were shifted away from the rotors. Each unit was thoroughly inspected prior to any remedial work to ensure damage was found early and repaired properly. An electrical engineer representing a generator manufacturer was summoned to the plant to assist with the evaluation.

The stator winding and core of each generator were carefully examined. The end windings, series connections, and circuit ring buses were manually compressed to check for tape separation and/or spongy insulation The stator windings appeared good; the insulation felt relatively solid, and no visible evidence of insulation damage was observed. The stator bore surfaces were moderately rusty but in good condition otherwise. Thus, the generators appeared salvageable, and a rehabilitation program was initiated. Benchmark insulation resistance measurements were made on the stator windings of the three units. Each phase was tested at 1000 V dc phase-to-ground. The 10-minute insulation resistance values ranged from approximately 80 to 100 kΩ.

Clean-Up

A low pressure steam cleaner was used to wash down the generator stators. A dilute solution of detergent was applied to remove oil and other filth. Nylon bristle brushes were used to gently scrub hard-to-remove dirt and rust deposits. Solvent residues were removed using a clean water rinse. The cleaning operation appeared to be very effective. The generators were allowed to air dry overnight before any electrical tests were performed.

Stator Winding Dry-Out

The Headgate Rock unit 1 stator winding was selected as the first unit to dry out. It was successfully heated using a combination of a 150,000 BTU/hour portable kerosene heater (salamander) for external heat, and a 460-volt, 30-kW direct current supply (i.e., dc welder) to generate internal heat. The three-phase stator winding was reconfigured from a wye-connection to a series-connection to allow the total welder output current to be circulated through the winding rather than being split between the three phases. All phase-to-phase and

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phase-to-welder connections were capable of handling 500 A continuously. The output current of the welder was varied to regulate the generator temperature. Depending on ambient conditions, approximately 450 A (or roughly 50 percent of rated stator current) was needed to maintain the maximum stator winding temperature.

The kerosene heater was placed in the lower stator area and its output ducted into the lower stator housing. Care was taken to prevent hot air from blowing directly onto the stator winding or circuit ring bus. Two fans were located in the lower stator housing to help circulate the heated air, and to remove water vapors. A tent comprised of two 30 by 60 ft plastic tarps joined lengthwise covered the entire generator to contain the heated air. The tent was vented to allow the moisture driven out of the windings to escape.

Temperature Monitoring

A resistance temperature detector (RTD) meter/calibrator was used to verify that the embedded stator winding resistance temperature devices (10.00 Ω copper at 25 °C) were not damaged during the flood. Numerous RTDs were tested and all were found to be functional. One RTD from each quadrant of the stator core was identified and selected for monitoring during the stator winding dry-out.

Due to the large thermal mass of the stator iron, the temperature of the stator end winding insulation rises much more rapidly than the temperature of the stator core. Accordingly, thermocouples were installed in various locations around the stator winding and core to monitor machine temperatures during dry-out. Upper and lower end windings, upper and lower circuit ring buses, stator core, and ambient temperatures were measured and recorded. Both RTD and thermocouple temperatures were monitored in order to maintain a uniform heat rise for safe drying. During dry-out, temperature readings were taken and recorded hourly.

Gases and vapors generated within the insulation by high temperature develop pressure and are forced through the insulation; this can break the continuity of the layers and cause delamination, or actually rupture the material [1]. The hottest temperatures occur at the copper conductor and can only be precisely determined by measuring the copper conductor resistance. Due to the inconvenience of this method, a temperature drop of 10 to 15 °C across the groundwall insulation is normally assumed. Therefore, if a maximum internal temperature of 90 °C is desired (based on the manufacturer's recommendations for Class F insulation), the corresponding maximum RTD temperature is 75 to 80 °C. Coils containing moisture are more susceptible to damage from overheating than they are when thoroughly dry; therefore, we established a maximum allowable RTD temperature of 75 °C. Because external temperatures will be lower than the temperature inside the stator slots, the surface (thermocouple) temperature limit was set at 65 °C. A maximum heating rate of 10 °C per hour was used.

Insulation Resistance Monitoring

A minimum insulation resistance of 5 MΩ at ambient temperature was required for the Headgate Rock stator windings to be considered suitable for high-voltage testing. Although, the insulation resistance of a completely dry winding is on the order of several hundred megohms, this value may not be reached until the unit has been returned to service and operated under load for some time. During dry-out, each stator winding phase was megger tested periodically to evaluate progress. A 1000-V dc test voltage was applied, and the 1-minute and 10-minute insulation resistance values were recorded along with the stator winding temperature.

To obtain the data needed to accurately normalize the insulation resistance measurements taken at various stator winding temperatures, a normalization curve was created for the generators as follows: After the stator winding had stabilized at its maximum temperature, the heat sources were turned off. When the RTD temperature dropped to 80 °C, a 1000-V megger test was quickly performed on each phase. The 1- and 10-minute insulation resistance values were recorded. The winding was allowed to continue to cool, and the megger tests were repeated at 60, 40 and 20 °C. The 10-minute results were averaged and plotted. A straight line fitted through the data yields the normalization curve for the Headgate Rock generator insulation system, as shown in Fig. 1. The conventional normalization curve found in IEEE Std. 43, *Recommended Practice for Testing Insulation Resistance of Rotating Machinery* [2] is also shown in Fig. 1 for comparison. The measured resistance versus temperature data demonstrate that the insulation resistance of the Headgate Rock groundwall insulation does not double for every 10-degree reduction in temperature as indicated in [2]. In fact, the winding temperature must be reduced by approximately 30 °C for the insulation resistance to double.

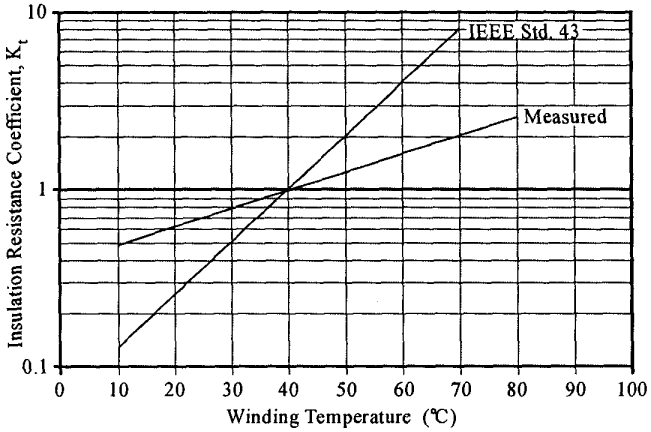

Fig. 1. Insulation resistance coefficient versus temperature.

III. RESULTS AND ANALYSIS

After the heat sources (i.e., dc welder and kerosene heater) were turned on, the temperature of the unit 1 stator winding was

increased above ambient. The temperature measurements indicated that the upper end winding surfaces were 10 to 15 °C hotter than the circuit ring bus, and approximately 3 °C above the stator core surface temperature as measured by thermocouple. The embedded stator RTD temperatures closely tracked the end winding temperatures as the winding was initially heated. After a few hours of continuous heating, the rate of increase of RTD temperatures was greater than that of the end winding temperatures. Eventually, the RTD temperatures stabilized at 10 to 15 °C above the end winding temperatures.

The unit 1 measured and normalized 10-minute insulation resistance values versus drying time have been plotted and are shown in Figs. 2 and 3, respectively. The insulation resistance measurements of Phases A and B were consistently lower than that of Phase C. No explanation for this difference has been found. (Interestingly, the subsequent dry-out and testing of unit 2 showed similar results.) After more than 3 weeks of dry-out, the unit 1 data indicates the insulation resistance has leveled off at approximately 1.5 MΩ for Phases A and B, and 4.5 MΩ for Phase C.

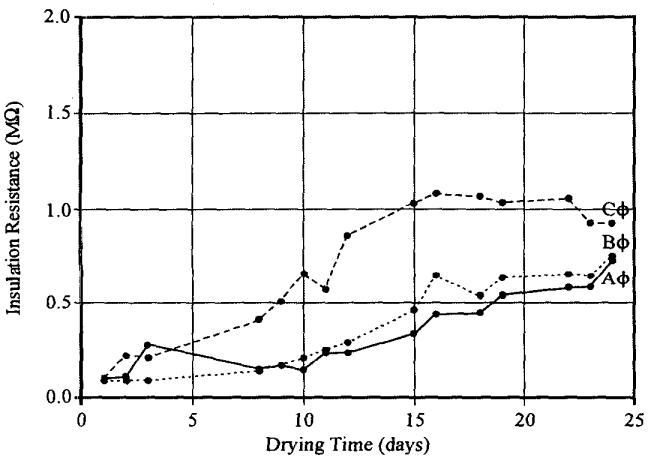

Fig. 2. Measured insulation resistance versus drying time.

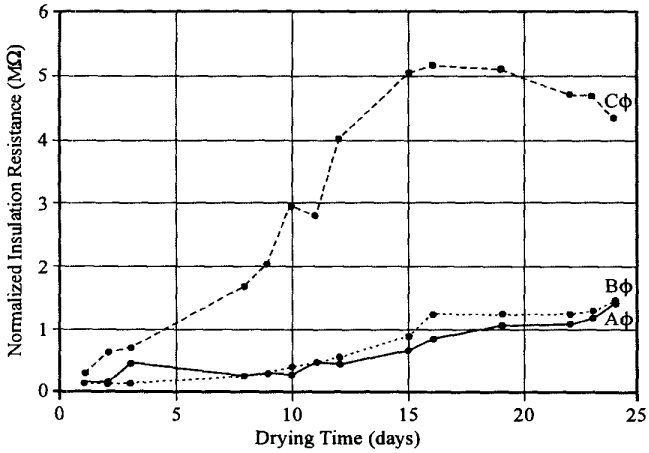

Fig. 3. Insulation resistance, normalized to 25 °C, versus drying time.

IV. CONCLUSIONS

The three Headgate Rock units will remain out of service until major repairs and replacement of other generator and plant equipment can be made. This is expected to take at least an additional 6 months. Up to now, the work on the generators has not impacted the overall schedule for bringing the powerplant back on line. But there is still doubt about the ability to return unit 1 to service in its present condition. The insulation resistance leveled off at a relatively low value despite several weeks of heating and drying. This could be an indication of trapped moisture. Also, the winding insulation may be comprised of polyester resin -- an hygroscopic material. Other utilities have reported difficulty in returning water-damaged polyester windings to service without subsequent failures. Given these facts, it was deemed prudent to further investigate the condition of the stator winding insulation prior to conducting pass/fail high-potential tests.

To this end, plans have been made to sectionalize the unit 1 stator winding by separating the winding parallel circuit leads from the ring bus. The insulation resistance of each parallel circuit and section of ring bus will be measured individually, allowing the insulation condition to be analyzed in more detail to determine whether the insulation resistance values are low due to the circuit ring bus, the stator winding coils, or both. These tests may also prove useful in evaluating whether the insulation resistance is low due to local or overall winding damage. The test results may also shed some light on the differences observed between the A, B, and C phase insulation resistance values.

After the megger tests are completed, high-voltage dc ramp tests will be performed on each of the circuit parallels as well as on the circuit ring buses. If no failures occur and the test results indicate the winding can withstand an ac voltage, a power factor tip-up test will be performed. And finally, an ac high-potential test will be conducted to ensure the winding is capable of withstanding operating voltage.

This test program is intended to provide the information needed to determine if the Headgate Rock stator windings are salvageable. The decision to rewind must be made quickly. It is unacceptable to extend the outage of the plant or to have a generator fail shortly after being returned to service. At the time of this writing, the unit 1 stator winding evaluation had not yet been completed. However, the results of the outlined evaluation will be available for the scheduled presentation.

REFERENCES

[1] *Rehabilitation of Flood Damaged Electrical Equipment*, Chapter 42, Westinghouse Electric Corporation.

[2] IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, STD. 43-1974.